# The Response of Wind Ripples to Long Surface Waves

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## LONG-TERM GOALS

To develop an advanced physical model of the wind wave spectrum based on the Donelan and Pierson (1987) approach and accounting for the nonlinear processes in the capillary-gravity range consistent with existing analytic models of high-wavenumber spectra.

To construct a new version of the air boundary layer (ABL) model coupled with wind waves using an advanced wind wave spectrum model and the approach developed by Makin et al. (1995).

To build a unified model of the short wave modulations by long surface waves. This model describes the reaction of the coupled system “wind waves –ABL” in the presence of surface disturbances caused by long waves.

To verify the model results on the available radar data and the new data obtained from the MHI Black Sea Research platform.

## APPROACH

The final shape of the wave spectrum is defined by competition of the coupling with the air boundary layer, wave-wave interaction (distributing energy and momentum across the spectrum), and dissipation through wave breaking and viscosity. The main objective of this study is to develop a unified physical model of the short wave modulation by a longer wave of an arbitrary origin taking into account the coupling of wind waves and the ABL, wave-wave interaction, and dissipation.

Recently a few “wind waves- ABL” coupled models have been proposed (e.g., Janssen, 1989; Chalikov and Makin, 1991; Makin et al., 1995). Kudryavtsev et al. (1997) have demonstrated that in such a coupled system a feedback mechanism can emerge between the modulated wind waves and the near surface wind stress variations. This mechanism is responsible for the strong modulation of wind ripples by a long surface wave. A scheme of the feedback action is the following: short waves affect the surface roughness, which determines the stress distribution. The stress in turn affects the short waves. The feedback mechanism acts along with the wave-current and wave-wave interactions to produce the hydrodynamic modulation of wind ripples. In recent years the nonlinear interaction processes have been studied intensively; e.g. Zakharov (1992) and Pushkarev and Zakharov (1996).

The coupling between wind waves and the air flow is sensitive to the wave spectral form in the full wave-number range, in particular to the high wave-number part. At the same time, the active microwave sensor return depends on the short surface waves scattering through the Bragg resonance mechanism. Hence, an advanced physical model of the wind wave spectrum has to be constructed.

## WORK COMPLETED

1. An advanced physical model of the short wind wave spectrum based on the Donelan and Pierson (1987) approach and accounting for the non-linear processes in the capillary-gravity range, viscous dissipation, dissipation due to wave breaking and generation of the parasitic capillaries, and wind input is constructed.

2. An advanced atmospheric surface boundary layer model directly coupled to wind waves using an advanced wind wave spectrum model developed under 1 and the approach developed by Makin et al. (1995) is constructed. The model describes the reaction of the coupled system ‘wind waves-atmospheric boundary layer’ in the case of undisturbed wind wave spectra.

3. An advanced model of short wind wave modulation by a long surface wave based on the coupled sea surface-atmosphere model developed under 2 is constructed. The model describes the reaction of the coupled system “wind waves-atmospheric boundary layer” in the presence of surface disturbances caused by long waves.

4. The wind wave modulation model results are verified on the new data obtained from the MHI Black Sea Research platform in the period June-July 1998, and September - October 1999.

## RESULTS

The wind over waves model is based on the approach developed by Makin et al. (1995). It is based on the conservation of momentum in the marine atmospheric surface boundary layer and allows relating the sea drag directly to the properties of the short wind waves. An assumption concerning the local balance of the turbulent kinetic energy production due to the mean and the wave-induced motions, and its dissipation allows us to reduce the problem to two integral equations: the resistance law above waves and the coupling parameter. To calculate the wave-induced flux the local friction velocity rather than the total friction velocity has to be used. In this case the growth rate parameter (dimensionless energy flux from wind to waves) depends on the coupling parameter. It is shown that the short gravity and capillary-gravity waves play a significant role in extracting momentum and are strongly coupled with the atmosphere. This fact dictates the use of the coupled short waves-atmosphere model in the description of the energy balance of those waves.

One of the key elements of the wind over waves coupled model is the advanced description of the wind forcing. To build the parameterization of the wind forcing new experimental results obtained by Donelan (1999) in the laboratory and new model results obtained by advanced wave boundary layer numerical model by Meirink and Makin (2000) were used. The refinement of the wave growth rate parameter has resulted from laboratory measurements (Donelan, 1999). Meirink and Makin (2000) have performed a study of the wave growth for low Reynolds number ($R_e$)air flow. In studies of the turbulent air flow over water waves it is usually assumed that the effect of viscosity near the water surface is negligible, i.e. the Reynolds number, constructed with the friction velocity and the wavelength, is considered to be high. However, for short waves or low winds this assumption is not valid. Therefore, a second-order turbulence closure that takes into account viscous effects is used to simulate the air flow. The model shows reasonable agreement with laboratory measurements of wave-induced velocity profiles. Next, the dependence of the dimensionless energy flux from wind to waves, or growth rate, on $R_e$ is investigated. The growth rate of waves that are slow compared to the wind is found to increase strongly. The numerical model predictions are in good agreement with analytical theories and laboratory observations. Results of the study are useful in field conditions for the short waves in the spectrum, which are particularly important for remote sensing applications.

A physical model of the short wind wave spectrum developed by Kudryavtsev et al. (1999) and incorporated into the atmospheric wind over waves coupled model developed by Makin and Kudryavtsev (1999) forms a coupled sea surface-atmospheric model. This model consistently describes the adjustment of waves to the atmosphere, and atmosphere to wind waves. Kudryavtsev et al. (1999), and Makin and Kudryavtsev (1999) further assess the evolution of this coupled system. It is shown that the measured statistical properties of the sea surface related to the short waves, such as the spectral shape of omni-directional and up-wind spectra, their energy level and wind speed dependence, angular spreading, and the wind speed dependence of integral mean square slope and skewness parameters, are well reproduced by the coupled sea surface-atmosphere model. The model reproduces as well the measured wind speed dependence of the drag coefficient and of the coupling parameter.

Kudryavtsev and Makin (1999) have developed a model of short wind waves (SWs) modulation by a long surface wave (LW). The idea behind this approach is that the air flow over the LW is affected by the varying (along the profile of the LW) surface roughness which is defined by the SW modulation. In turn, the SWs are coupled to the air flow through the variation in the surface stress which modifies the SW growth rate along the LW. This provides the feedback between the air flow and short waves in presence of the long wave. In order to construct the model of the SW modulation the resistance law above waves has to be defined. In principle, it follows from the wind over wave coupled model (Makin and Kudryavtsev, 1999). However, at this stage it was realized that separation of the air flow from breaking waves plays a significant role in the air-sea interaction, especially at moderate to high winds. Makin and Kudryavtsev (1999) did not account for this effect. The model of the wind over wave coupling accounting for this effects follows from Makin and Kudryavtsev (1999), and was developed by Kudryavtsev and Makin (1999).

The model describes the impact of the air flow separation (AFS) from wave breaking fronts on the sea surface drag. Wave breaking fronts are modeled by the discontinuities of the surface slope. It is assumed that dynamics of the AFS from breaking crests is similar to that from the backward facing step. The form drag supported by an individual breaker is described by the action of the pressure drop distributed along the forward face of the breaking front. The total stress due to the AFS is obtained as a sum of contributions from breaking fronts of different scales. To that end the statistical properties of breaking fronts are described by the approach developed by Phillips (1985). Outside the breaking fronts the viscous surface stress and the wave-induced stress support the drag of the sea surface. The model forms a self-consistent dynamical system sea surface-atmosphere where the air flow and wind waves are strongly coupled. It is shown that the dimensionless Charnock parameter (roughness scale normalized on the square of the friction velocity and the acceleration due to gravity) increases with the increase of the wind speed in agreement with field measurements. The stress due to the AFS normalized on the square of the friction velocity is proportional to the cube of the wind speed. At low winds the viscous surface stress dominates the drag. At moderate and high winds the form drag dominates. At the wind speed higher than 10 m/s the stress supported by the AFS becomes comparable with the wave-induced stress and supports up to 50% of the total stress.

This model is applied for the hydrodynamic part of the radar MTF. The hydrodynamic MTF is defined as a residual between the total radar MTF and the tilt MTF. The main conceptual assumption is made that the hydrodynamic MTF results not only from the modulation of short waves, which provide the Bragg scattering, but also from the modulation of the sea surface patterns, for example, breaking waves that could provide the non-Bragg scattering. It is commonly accepted that the non-Bragg scattering from breaking waves contributes to the total VV and HH normalized radar cross section (NRCS) even at moderate incidence angles. Although this contribution may be small, the strong modulation of wave breaking forms a significant contribution to the hydrodynamic MTF. A semi-empirical model of VV and HH NRCS and its modulation by the LW (hydrodynamic MTF) is proposed. This model relates the NRCS and its modulation to the SW spectrum and wave breaking parameters resulting from the developed sea surface-atmosphere model.

Model estimates of the hydrodynamic radar MTF are compared with available radar observations. The comparison shows that the MTF based on the Bragg model is unable to reproduce the observed residual MTF (the difference between the observed total MTF and the tilt MTF) and its dependence on the polarization. Accounting for the non-Bragg scattering provides the model hydrodynamics MTF in reasonably good agreement with observations.

Two field experiments to study the modulation of waves were performed from the MHI Black Sea Platform. Experimental data obtained during the field campaigns in June-July of 1998 and in October of 1999 include:

1. Microwave backscatter by Ku and Ka-band, HH and VV polarized radar, with wavelengths of 1.2 cm and 0.8 cm;
2. Wave records by an antenna of wire wave gauges;

3. Wind velocity above the instantaneous sea surface at z = 0.15 m and 0.65 m done from a small wave following buoy;

4. Wave breaking parameters obtained by an optical system;

5. Wind speed and the air temperature at z = 21 m and 5 m, and the sea surface temperature.

These data were processed and analyzed. The results can be summarized as:

1. The residual (hydrodynamic) part of the Ku and Ka-band radar MTF increases with decreasing wind speed and decreasing frequency of the modulating LW. The phase of the MTF is close to the LW crest with a small shift towards the forward face of the LW slope for observed wind speeds in the range of 5 m/s to 12 m/s. The experimental estimates of the MTF amplitude exhibit clear polarization dependence and dependence on inverse age of the modulating LW.

2. The wind speed variation induced by long waves just above the wavy surface was revealed experimentally. The amplitude of the normalized wave-induced wind speed variation (the so-called wind MTF) is found to be in the range of 0.5 to 10 depending on the angle between the LW and the wind direction. The highest magnitude of the wind MTF was observed at low wind speeds when long waves were running opposite to the wind. Experimental measurements show that wave breaking is strongly modulated along the LW. In terms of MTF the modulation estimate is about 20. This means that wave breaking can significantly contribute to radar MTF.

3. The experimental estimates of the wind MTF were compared with model predictions based on the TAF model. Good agreement is shown. The modeled surface stress modulation being in reasonable agreement with observed one, however cannot provide the observed values of radar MTF when the Bragg NRCS model is applied. It is shown that the observed radar polarization ratio significantly differs from the Bragg model prediction, which confirms that the radar signal is affected by the non-Bragg scattering. Model estimates of radar MTF done on a basis of the coupled 'wind-wave' model and the semi-empirical NRCS model are in a good agreement with observation.

## IMPACT/APPLICATIONS

The impact of this work will be most immediately felt in the radar remote sensing community, where a complete model of the capillary-gravity waves, founded on sound physical principles and verified against field and laboratory data, is sorely needed. Other applications are in understanding and parameterizing such critical air-sea exchanges as gas transfer, momentum and heat transfer.

## TRANSITIONS

None yet.

## RELATED PROJECTS

The new Air-Sea Interaction Salt-water Tank (ASIST) facility on the campus of the Rosenstiel School of the University of Miami has the necessary delicate measuring capability to benefit from and further test the model being developed here.

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